

On the transition from nuclear-cluster to black-hole dominated galaxy cores

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ABSTRACT

Giant elliptical galaxies, believed to be built from the merger of lesser galaxies, are known to house a massive black hole at their center rather than a compact star cluster. If low- and intermediate-mass galaxies do indeed partake in the hierarchical merger scenario, then one needs to explain why their dense nuclear star clusters are not preserved in merger events. A valuable clue may be the recent revelation that nuclear star clusters and massive black holes frequently *co-exist* in intermediate mass bulges and elliptical galaxies. In an effort to understand the physical mechanism responsible for the disappearance of nuclear star clusters, we have numerically investigated the evolution of merging star clusters with seed black holes. Using black holes that are 1-5% of their host nuclear cluster mass, we reveal how their binary coalescence during a merger dynamically heats the newly wed star cluster, expanding it, significantly lowering its central stellar density, and thus making it susceptible to tidal destruction during galaxy merging. Moreover, this mechanism provides a pathway to explain the observed reduction in the nucleus-to-galaxy stellar mass ratio as one proceeds from dwarf to giant elliptical galaxies.

Subject headings: black hole physics — galaxies: structure — galaxies: nuclei — galaxies: evolution

1. Introduction

The central regions of inactive galaxies are receiving increasing attention as astronomers begin to accurately quantify their inner-most features. These range from partially evacuated cores housing a massive black hole (MBH) in giant galaxies to excess light in the form of a dense nuclear star cluster (NC) in less massive spheroids¹. Curiously, an unexpected connection between MBHs and NCs is starting to emerge (Ferrarese et al. 2006a; Wehner & Harris 2006; Balcells et al. 2007; Graham & Spitler 2009).

At the low mass end, dwarf elliptical (dE) galaxies are frequently observed to contain a dense cluster of stars near their centre (e.g. Sandage & Binggeli 1984; Binggeli et al. 1985; Ferguson & Binggeli 1994). The stellar mass of these NCs relative to their host spheroid’s stellar mass is known to systematically decrease as the dE mass increases (e.g. Graham & Guzmán 2003; Grant et al. 2005).² Therefore, if nucleated elliptical galaxies are players in an hierarchical Universe (White & Rees 1978), one cannot simply merge such galaxies and double the mass of the new host galaxy and its NC.

At the high mass end are massive elliptical galaxies — the end product of major mergers. However, such galaxies are observed not to contain NCs, instead they possess central stellar deficits relative to the inward extrapolation of their outer Sérsic light profile (e.g. Graham et al. 2003; Trujillo et al. 2004; Graham 2004; Ferrarese et al. 2006b). While it has been advocated that the dry merging of elliptical galaxies will result in the partial evacuation of the new galaxy’s core due to the binary coalescence of pre-existing MBHs (Begelman et al. 1980; Ebisuzaki et al. 1991; Milosavljević & Merritt 2001; Merritt & Milosavljević 2005; Merritt et al. 2007), there must be more going on. There must be a phase which erases the NCs — not included in the above mentioned studies — that are prevalent in the less massive progenitor galaxies. While Berczik et al. (2005) used Plummer models to represent galaxies in their detailed analysis of the impact that binary MBHs can have, here we dramatically rescale the problem, using Plummer models to represent NCs that are $\sim 10^3$ times smaller and, globally, $\sim 10^5$ times denser than galaxies.

Our motivation arises because it has recently been recognised that intermediate mass elliptical galaxies, and the similarly massive bulges of disc galaxies, regularly contain both a NC and massive black hole (e.g. Graham & Driver 2007; González Delgado et al. 2008; Seth

¹The term spheroid is used to denote either an elliptical galaxy or the bulge of a disk galaxy.

²The bulges of disc galaxies also commonly contain a NC (e.g., Philips et al. 1996; Carollo, Stiavelli & Mack 1998; Böker et al. 2002), and the same general trend in the nuclear-to-spheroid stellar flux ratio is observed (e.g., Balcells et al. 2003, 2007).

et al. 2008). Graham & Spitler (2009) have quantified how the $M_{\text{BH}}/M_{\text{NC}}$ mass ratio (F_{BH}) increases with increasing host spheroid stellar mass, M_{sph} , until only a MBH is present at the centre. While the runaway merger of NC stars during a merger event may lead to their conversion into a MBH (e.g., Zel’dovich & Podurets 1965; Frank & Rees 1976; Quinlan & Shapiro 1987; Lee 1993), and feedback processes may also impact F_{BH} (McLaughlin et al. 2006; Nayakshin et al. 2009), this Letter explores whether dense NCs with seed MBHs might evaporate during a collision due to dynamical heating by the MBHs.

2. The model

Working from an established N -body code (Bekki et al. 2004; Bekki 2010) which runs on the GRAvity PipE (Sugimoto et al. 1990), we have developed an idealized model in which a new single NC can be formed from the collisionless merger of two NCs with MBHs — an event likely to occur during a major galaxy merger (e.g., Bekki 2007a; Bekki et al. 2010 in preparation). Here we investigate how the final structure of the new NC depends on the mass ratio $M_{\text{BH}}/M_{\text{NC}}$ ($= F_{\text{BH}}$) of the initial NCs. We assume that the dynamical evolution of the two NCs are dominated by the NCs and MBHs themselves, rather than by the gravitational field of background stars. Thus, each of the present models includes only two NCs and two MBHs: it includes neither background field stars nor external tidal fields of galaxy mergers.

The total mass and size of an initial NC are represented by M_{NC} and R_{NC} , respectively. All masses and lengths are measured in units of M_{NC} and R_{NC} unless otherwise specified. Velocity and time are measured in units of $v = (GM_{\text{NC}}/R_{\text{NC}})^{1/2}$ and $t_{\text{dyn}} = (R_{\text{NC}}^3/GM_{\text{NC}})^{1/2}$, respectively, and the gravitational constant G is assumed to be 1. If we adopt $M_{\text{NC}} = 5.1 \times 10^6 M_{\odot}$ and $R_{\text{NC}} = 77 \text{ pc}$ as fiducial values — corresponding to $\omega \text{ Cen}$ (e.g., Meylan et al. 1995), which is considered to originate from a nucleated galaxy (e.g., Bekki & Freeman 2003) — then $v = 16.9 \text{ km s}^{-1}$ and $t_{\text{dyn}} = 4.46 \times 10^6 \text{ yr}$. The gravitational softening length, ϵ_{g} , is set equal to the mean separation of stellar particles at the half-mass radius³ of the initial NC: $\epsilon_{\text{g}} = 0.01R_{\text{NC}}$ ($=0.77 \text{ pc}$). This softening length is also adopted for the MBHs.

The radial density profile of our preliminary NC is given by a Plummer model with scale length set equal to $0.2R_{\text{NC}}$. We will explore in detail how the present results depend on models with different initial radial profiles (e.g., King or Sérsic models) in future work. To construct a model in dynamical equilibrium for a NC with a MBH located at its center, we adopt the following two steps. First, the initial mass of the MBH in our isolated NC model is set to the mass of each individual star (m_{star}) in the NC. Second, we run the isolated

³The half-mass radius equals $0.25R_{\text{NC}}$.

model such that the initial MBH mass (m_{star}) is increased steadily and slowly to finally reach any adopted M_{BH} value within $20 t_{\text{dyn}}$ (i.e., adiabatic growth of the MBH). During this isolated evolution of the NC, the stellar distribution of the NC can adiabatically evolve into a new dynamical equilibrium. We then use this new radial distribution of the stars for our progenitor NCs which are subsequently merged.

We have confirmed that with time steps as small as 4.5×10^4 yr for models with $F_{\text{BH}} \leq 0.025$, the NCs with MBHs are stable after $20 t_{\text{dyn}}$. The changes to the central stellar densities due to adiabatic MBH growth in models with MBHs are only a factor of ~ 2 in comparison with those with no MBH. This effect is much smaller than the factor of ten change in central stellar density due to MBH heating, as shown later. We are therefore able to probe the effects of MBHs in NC merger remnants on the inner stellar densities of the remnants.

The two NCs in a NC merger are referred to as NC1 and NC2 and the relative positions and velocities of NC2 with respect to NC1 are set to be (X_r, Y_r, Z_r) and (U_r, V_r, W_r) , respectively. Although the relative positions and velocities of NC2 are free parameters, and we investigated models with different values for these 6 parameters, we only show the results of the models with $(X_r, Y_r, Z_r) = (4, 0.5, 0)$ and $(U_r, V_r, W_r) = (-1, 0, 0)$. The total number of stellar particles used in a model for NC merging is 4×10^5 , allowing us to conduct a large parameter study (e.g., F_{BH} and Y_r , and U_r) for NC evolution with MBHs. We follow the dynamical evolution of two merging NCs for $20 t_{\text{dyn}}$ within which the two NCs merge with each other completely to form a new NC.

The two MBHs in the newly formed NC can drift around the central region of the NC after the BHs form a very close pair owing to their orbital decay caused by dynamical friction against the NC stars. We note that a Newtonian gravitational force is always assumed (outside of ϵ_g) during simulations with GRAPE (we do not investigate MBH merging through gravitational wave radiation). We assume that the MBH pair can merge to form a single MBH akin to the merging of stellar-mass BHs in dense star clusters (e.g., Quinlan & Shapiro 1989) and adopt the following two steps to obtain the final stellar distribution in the NC merger. First, the MBHs in the merger remnant are replaced with a single MBH with position and velocity equal to the mass center of the two MBHs. This is done after $20 t_{\text{dyn}}$, when the single NC is already formed and dynamically relaxed. Second, we follow the evolution of the NC merger remnant with the new MBH for a further $20 t_{\text{dyn}}$ of the original NCs, so that the single MBH can sink into the center of the remnant due to dynamical friction and the stellar distribution can change in response. We use this final stellar distribution for the investigation of the radial density profile of the NC merger.

The above models are referred to as “single merger models”. We also ran “sequential

merger models” in which radial density profiles of stars in stellar remnants of two and three sequential NC mergers are investigated. The progenitor NCs of the second NC merger are the remnant of the first NC merging, and those of the third sequential merger are the remnant of the second sequential NC merging, with one key difference being that these mergers are not evolved for $20 t_{\text{dyn}}$ between successive mergers. In order to better understand the physical role of dynamical heating on NCs by MBHs, we also ran single and sequential merger models with no MBHs (i.e., $F_{\text{BH}} = 0$).

The present study can be compared with Ebisuzaki et al. (1991) who investigated the radial density profiles of elliptical galaxies formed from galaxy merging with MBHs. Although they did not investigate the dynamical influence of MBHs on NCs, they clearly pointed out that MBHs can lower the inner densities of giant ellipticals because of the dynamical effects of MBHs (Begelman et al. 1980). One of the significant differences between their work and ours is that we explore models with much larger F_{BH} (up to 0.05, although see Kandrup et al. 2003).

3. Results

Fig. 1 shows that the final internal (three-dimensional, 3D) radial density profiles $\rho_{\text{NC}}(r)$ are significantly different between our four single merger models with different F_{BH} . The final central 3D densities depend on F_{BH} such that they are lower in models with larger F_{BH} . For example, the inner stellar density at $r/R_{\text{NC}} = 0.05$ ($\log r/R_{\text{NC}} = -1.3$) in the model with $F_{\text{BH}} = 0.05$ is a factor of ~ 32 lower than that in the model with $F_{\text{BH}} = 0$ (i.e., with no MBH). This reflects how dynamical heating of NCs, by MBHs during NC merging, expels stars from the central regions and consequently lowers the inner stellar densities of newly wed NCs. A significant fraction of stars initially within R_{NC} can be relocated well beyond $R = 5R_{\text{NC}}$: the fraction can be as large as 0.37 in models with $F_{\text{BH}} = 0.05$. Moreover, the internal radial density profiles of merger remnants, for $r/R_{\text{NC}} \leq \sim 1/4$, are shallower in models with larger F_{BH} . These results clearly demonstrate that MBHs (F_{BH}) can control the stellar structure in (collisionless) mergers of NCs owing to dynamical heating by MBHs.

To understand why the stellar mass densities in models with MBHs can be significantly smaller than those without MBHs (as shown in Fig. 1), we ran comparative models with $F_{\text{BH}} = 0.01$ in which only NC1 had a MBH (i.e., $F_{\text{BH}} = 0$ for NC2). Fig. 2 shows that the merger model with a MBH only for NC1 has a significantly higher central density than that in the model with MBHs in both NC1 and NC2. This strongly suggests that dynamical heating from binary MBHs sinking into the merger remnant of the two NCs is important in reducing the inner density of the remnant. We also observe that the merger model with a

MBH only for NC1 has a smaller inner stellar density in comparison with the model with no MBH, revealing that a single MBH can also heat up the remnant to some extent as it sinks to the center.

Fig. 3 illustrates that the final stellar profile of the three sequential major merger events with $F_{\text{BH}} = 0.025$ has a significantly lower central density than when $F_{\text{BH}} = 0$ (i.e., no MBH; compare Figure 1 by Makino & Ebisuzaki 1996). Fig. 3 also reveals that the inner stellar densities of NC merger remnants in the sequential model with $F_{\text{BH}} = 0.025$ can become progressively lower as NC (and possibly inspiraling globular cluster) merging proceeds: the central stellar density in the final merger remnant (i.e., after three sequential merger events) is a factor of ~ 16 smaller than in the original NC for this sequence.

Fig. 4 shows that ρ_{NC} at $r = 0.05R_{\text{NC}}$ is lower in the sequential merger models with larger F_{BH} owing to stronger dynamical heating. We do however note that the model with $F_{\text{BH}} = 0.01$ does not show a significant decrease of its stellar densities at $r = 0.2R_{\text{NC}}$ owing to the much less effective dynamical effects of the MBHs on the NCs. This is in accord with the binary MBH scouring of the core regions in massive elliptical galaxies, in which the loss cone typically dominates only the inner few percent of the stellar distribution (e.g., Trujillo et al. 2004). These simulations also suggest that larger, more massive NCs will be more difficult to observe as distinct NCs as their stellar densities may become comparable or less than that of their host galaxy. Furthermore, Fig. 4 shows that ρ_{NC} at $r = 0.2R_{\text{NC}}$ (corresponding to the scale-radii of the original NCs) is lower in the sequential merger models with larger F_{BH} , though the dependence is weaker than that of ρ_{NC} at $r = 0.05R_{\text{NC}}$ on F_{BH} . This result implies that more massive NC merger remnants with lower central densities are more susceptible to tidal destruction by the external gravitational fields of their host galaxies owing to their lower mean stellar densities.

4. Discussion and conclusions

So far we have focused on the internal density profiles of NCs and have not discussed their *projected* (two-dimensional, 2D) radial density profiles, which can be directly compared with recent observational studies for (i) the origin of the apparent MBH-NC connection (e.g., Côté et al. 2006) and (ii) the observed $F_{\text{BH}} - M_{\text{sph}}$ relation (Graham & Spitler 2009). Fig. 5 reveals that the *projected* radial density profiles of NC merger remnants, $\Sigma_{\text{NC}}(R)$, are significantly different between our four models with different F_{BH} . The rather low central Σ_{NC} value at $R = 0.05R_{\text{NC}}$ and shallow inner density profile, in the model with $F_{\text{BH}} = 0.05$ suggests that if this merger remnant is located in the central region of a galaxy, it is less likely to be observed as a distinct NC. While the order of magnitude drop in surface density

may seem like overkill, especially given the apparently small levels of excess nuclear light seen in most resolution-limited images, we note that well-resolved galaxies can have NC light up to $5 \text{ mag arcsec}^{-2}$ ($100\times$) brighter than the underlying galaxy (e.g., Graham & Spitler 2009).

The present study confirms that more evolved NCs — by which we mean NCs, with MBHs, that are further along the merger tree — can have lower inner densities (ρ_{NC} and Σ_{NC}) and shallower inner 2D density profiles than their progenitors. This suggests that boundaries between distinct stellar nuclei and background field stars in galaxies are less clear for more evolved systems as the NCs are effectively washed-out and dissolve into the host galaxy. Such diffuse NCs are also more susceptible to tidal destruction during galaxy merging. The present study therefore suggests that the observed $f_{\text{BH}}\text{-}M_{\text{sph}}$ relation can be understood in terms of the structural evolution of merging NCs with MBHs.

Measurements of partially-depleted galaxy cores, relative to a galaxy’s outer light-profile, have revealed a correlation between the central stellar mass deficit and the luminosity of the host spheroid and its MBH mass (e.g., Graham 2004; Ferrarese et al. 2006b). As detailed in Graham & Guzmán (2003) and Côté et al. (2007), the transition between massive galaxies with partially-depleted cores and those without — which frequently have excess nuclear light instead — occurs around $M_B = -20.5 \text{ mag}$. Previous numerical simulations proposed that the origin of these central stellar deficits can be understood in the context of core formation through dynamical heating of stars by inspiralling MBHs in galaxy merging (e.g., Ebisuzaki et al. 1991). The present study has, for the first time, addressed one of the overlooked problems related to the nuclear structures of galaxies: why and how can dense NCs disappear during galaxy growth through galaxy merging ?

We advocate here that core-depletion due to the gravitational slingshot of host galaxy stars by inspiralling MBHs will not occur in earnest until the NCs surrounding the MBHs have first been eroded away by this same mechanism: once the NCs are effectively gone, the binary MBHs, perhaps from additional merger events, can then commence to eat into the inner light profile of the host galaxy to produce the observed partially-depleted cores. This important step can explain why NCs disappear along the spheroid mass sequence and it also offers a process through which to understand the observed $F_{\text{BH}}\text{-}M_{\text{bulge}}$ relationship in terms of galaxy formation within the hierarchical merging scenario.

The present study suggests that if NCs in low-mass galaxies have seed MBHs, then their inner densities should progressively decline as galaxies grow through merging. This is at odds with the simple superposition of the NC density field for merging NCs without MBHs (Fig. 3, lower panel). Although many previous theoretical studies investigated how NCs are formed, either by merging of SCs (e.g., Tremaine et al. 1975; Capuzzo-Dolcetta

& Miocchi 2008) or by dissipative gas dynamics in galaxies (e.g., Bekki et al. 2006; Bekki 2007b), they did not predict (i) how BHs can be formed in NCs and (ii) what a reasonable value is for F_{BH} . The formation of seed MBHs *within NCs* may be different from that of intermediate-mass BHs in *isolated* globular clusters through merging of stellar-mass black holes (e.g., O’Leary et al. 2006), because the deeper gravitational potential wells of the NC host galaxies would play a role in retaining interstellar gas more efficiently. It is thus our future study to investigate how seed MBHs can be formed in NCs at the epoch of NC formation in low-mass galaxies based on more sophisticated numerical simulations.

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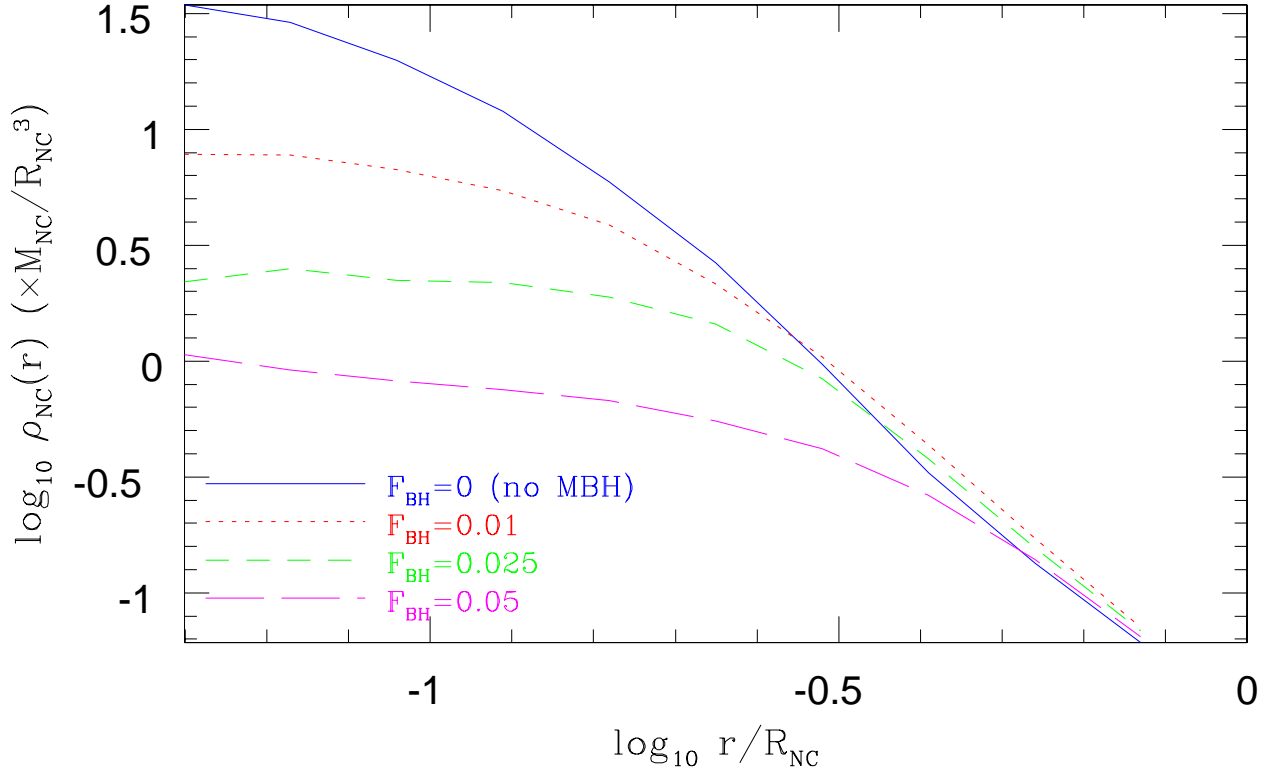


Fig. 1.— Final radial density profiles of NCs, $\rho_{\text{NC}}(r)$, at an epoch $20t_{\text{dyn}}$ after MBH coalescence for four different single merger models. Note that the inner densities become smaller for NC mergers with higher mass fractions of MBHs (i.e., larger F_{MBH}).

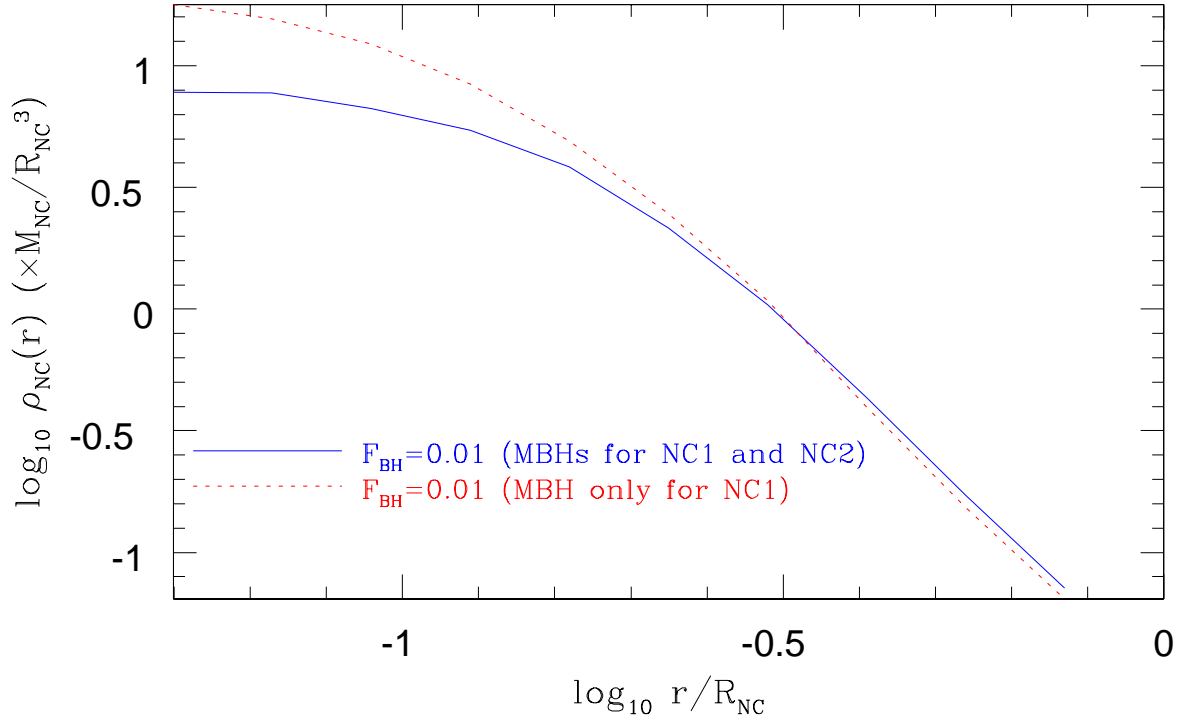


Fig. 2.— Same as Fig. 1 but for models with a MBH only for NC1 (red dotted) and with MBHs both for NC1 and NC2 (blue solid). For these models, $F_{\text{BH}} = 0.01$ is used.

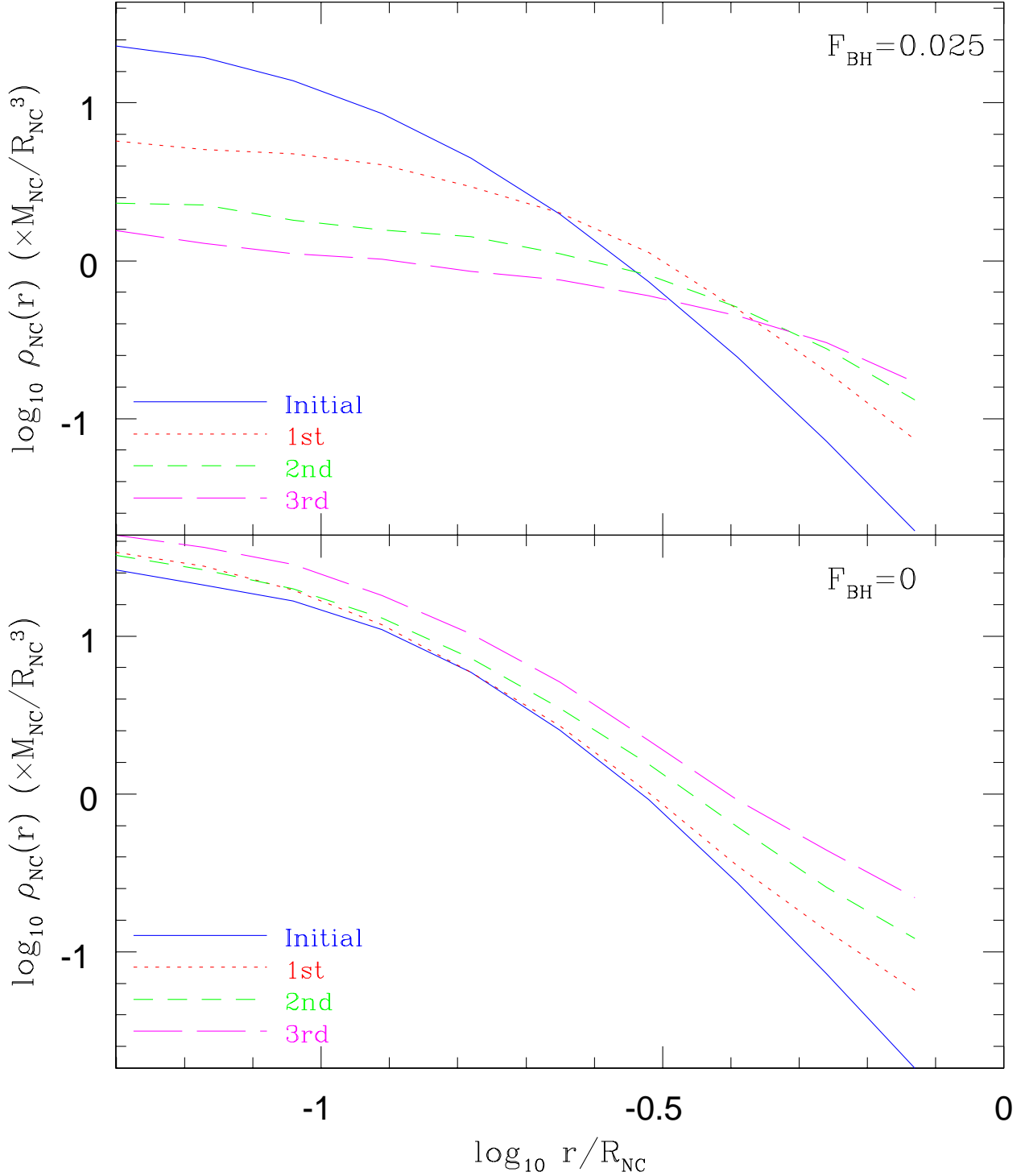


Fig. 3.— The same as Fig. 1 but for two sets of sequential models. The radial stellar distributions for the initial NCs, the 1st merger remnant, the 2nd, and the 3rd are shown by the blue solid, red dotted, green short-dashed, and magenta long-dashed lines, respectively. The initial profiles are slightly different between the two sequential models because the initial radial profile in the model with $F_{\text{BH}} = 0.025$ is the profile $20t_{\text{dyn}}$ after adiabatic growth of the single MBH. The dotted line in the upper panel can be different from the short-dashed line in Fig. 2 for $F_{\text{BH}} = 0.025$, because the results of the model in this figure are just after merging of NCs.

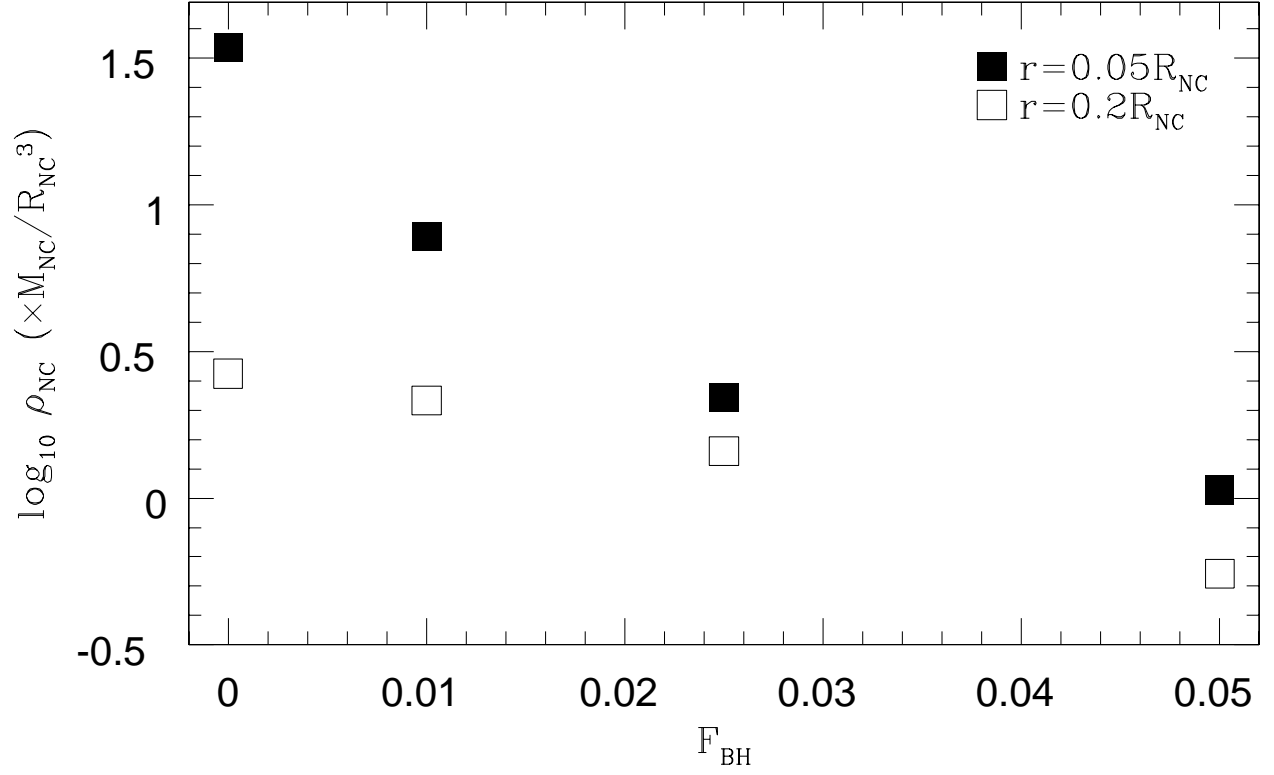


Fig. 4.— The dependence of final stellar densities (i.e., those from the 3rd merger remnants) at $r = 0.05 R_{\text{NC}}$ (filled squares) and at $r = 0.2 R_{\text{NC}}$ (open squares) on the initial F_{BH} mass ratio.

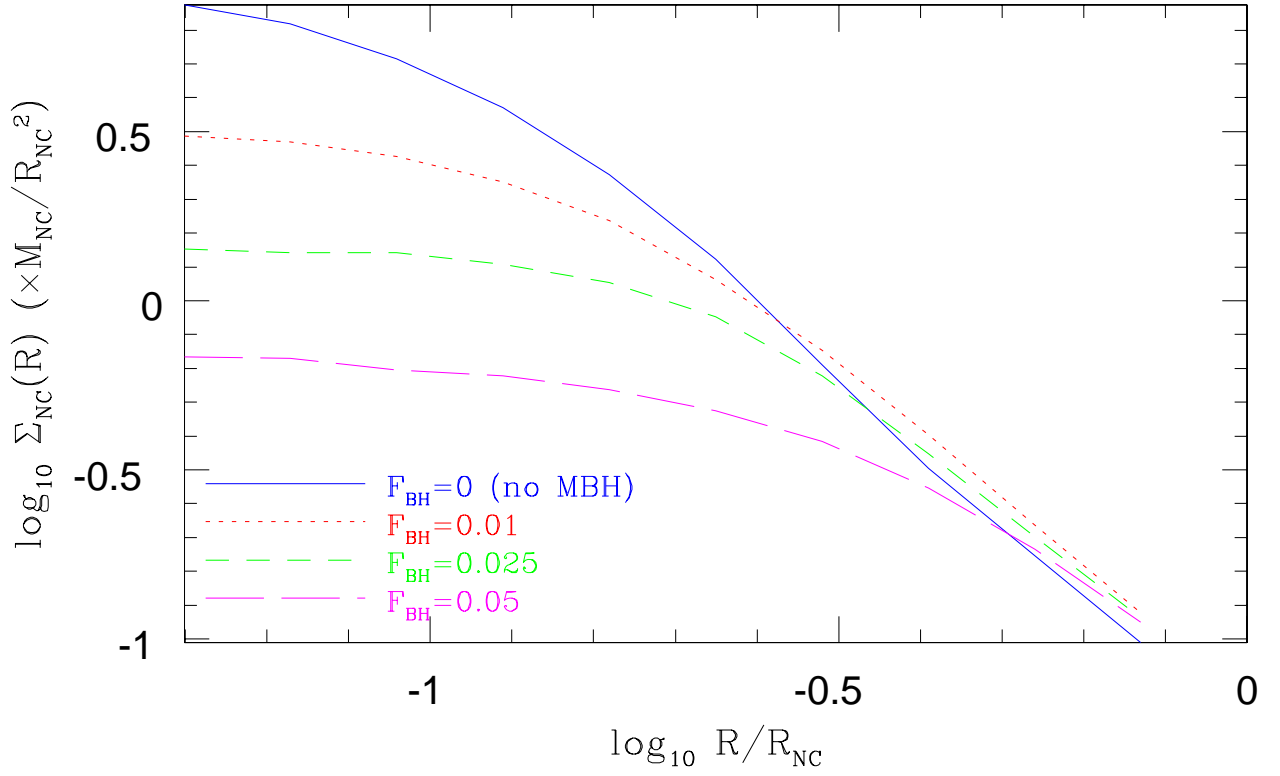


Fig. 5.— The projected radial density profiles, $\Sigma_{\text{NC}}(R)$, for four different single merger models with $F_{\text{BH}} = 0$ (blue solid, i.e., no MBH), $F_{\text{BH}} = 0.01$ (red dotted), $F_{\text{BH}} = 0.025$ (green short-dashed), and $F_{\text{BH}} = 0.05$ (magenta long-dashed).